A Comprehensive Methodology to Define Threshold Values of Pavement Performance Indicators

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ABSTRACT: In the frame of a rational management of a road network, road operators and transportation authorities attempt to define threshold values of acceptance for pavement surface characteristics. This procedure is either based on relevant experience or drawn from a combination of subjective ranking and monitoring data. Rare are the references of an analytical procedure to define these threshold values with respect to the operational criteria of a road network: safety, comfort, environment, economy. Several road management agencies worldwide apply specific limit values for each pavement feature. Conversely, other authorities do not prescribe acceptance limits at all, considering high variability of local factors such as traffic and climatic conditions. In either case, the analytical approach to reliably define limit values is missing. In this paper, a methodology to provide threshold values for pavement surface characteristics is presented. Three most important measurable characteristics of pavement condition, skid resistance, roughness and rutting, are herein analyzed. This analysis is carried out by introducing respectively suitable parameters, namely, the sideway force coefficient (SFC), the international roughness index (IRI) and the rutting depth (RD). The objective is to outline a comprehensive methodology for determining threshold values for indicators that portray pavement condition. The proposed methodology attempts to define these limit values by spotting abrupt change in term of safety or significant increase of negative effects to road users. Relative graphs are given for the aforesaid characteristics correlated with safety or cost data, providing evidence of this "inflection point", adequately interpreted to provide the threshold values in question.

KEY WORDS: Pavement, threshold, maintenance, comfort, safety.

1 INTRODUCTION

Rigorous application of limit allowable values of pavement characteristics is a wide and controversial issue. It is generally accepted that limit values depend on various parameters, namely the purpose of monitoring and the criteria adopted. Besides, it is obvious that different limit values must be used at different road categories or, even, at different road segments with regard to accident risk and ride discomfort.

Several transportation agencies apply minimum limit values of pavement friction that define the lowest acceptable level of safety before restoration. For example, the states of Maine, Washington, and Wisconsin use 35, 30, and 38, respectively, as cutoff values for

SFC_{50} (Henry 2000). Meanwhile, Minnesota uses 45 as limit value. In Europe, SFC_{50}=50 applied as minimum value for specific road segments. This variation of the lower limit of SFC is the outcome of difference in engineering approach utilized by road managing authorities. The lower limit of skid resistance value designates the minimum acceptable level of safety with regard to road friction.

In 2000, a decision made by Missouri courts in a case where two vehicle collided because of poor skid resistance demonstrated the need for acceptable friction levels by pavement maintenance (Missouri Court Affirms Award 2003). The court ruled that it is the responsibility of the State DOT to improve skid resistance and/or warn the motorist that the highway is slippery to prevent accident of this nature. Nonetheless, Federal Highway Administration (FHWA) has convened specifying a minimum friction level (Henry 2000). It was generally admitted that every State is best qualified to determine the conditions most appropriate to face vehicle skidding problems. Austroads recently stated that no straightforward method exists for defining a skid resistance value at which a site automatically transforms from being “safe” to “hazardous” (Austroads 2005).

The purpose of this paper is to outline a concrete methodology producing limit values of skid-resistance (SFC), roughness (IRI) and rutting (RD) for road pavements under traffic according to well established criteria of road safety and economy. These pavement characteristics are supposed to better represent the overall road performance and to be adequately related to road accident and cost data by means of mathematical formulas.

2 CONCEPT FOR DEFINING LIMIT VALUES OF PAVEMENT CHARACTERISTICS

The “limit value” of a pavement feature, hereby considered as a pavement performance indicator (e.g. Sideway Force Coefficient [SFC], International Roughness Index [IRI], Rut Depth [RD]), is defined as the minimum or maximum acceptable value of the relevant property (e.g. skid-resistance, evenness, rutting) for a road under traffic. It is generally convened that beyond the said value, there is a sudden change in the level of service of the road and the negative effects to safety and comfort are much more intense. Within this context, the procedure to define limit values of pavement performance indicators, at the operational stage of a road consists of the following steps:

- Mathematical formulas relating pavement characteristics (SFC, IRI, RD) with safety and travel time features are proposed. These formulas may be the most well-established experience-based correlations quantifying the impact of pavement surface deterioration with regard to safety and economy. To this effect, road safety is portrayed through the accident rate parameter (*r*) and travel time or economy is expressed by the Travel Time Cost (TTC).

- Limit values of the specific characteristics are defined at the inflection point of respective curves indicating an abrupt change, a severe lack of safety (in terms of accident rate) or an important increase of users cost (in terms of TTC). These limit values may vary with regard to the functional classification of road, the traffic volume and the percentage of heavy vehicles.

3 RELATION BETWEEN PAVEMENT CHARACTERISTICS AND CRASH RISK, USERS COST

3.1 Relation between Skid Resistance and Crash Risk

Although most vehicle crashes involve multiple causative factors, crash investigations have consistently shown a link between crashes and pavement surface conditions/characteristics, such as friction and texture. It seems, therefore, that there is a need for in-depth knowledge and understanding of the effect of slipperiness to road safety and for effective solutions to potentially hazardous situations.

While the exact relationship between wet-weather crashes and pavement friction is difficult to quantify, research on traffic accidents has shown that the number of wet crashes increases as pavement friction decreases (all other factors, such as speed and traffic volume, remaining the same).

In a road safety study (Rizenbergs et al. 1972), crash data and measured pavement friction values obtained from rural interstates and parkway roadways in Kentucky were analyzed. The results of the analysis showed increased wet crash rates at pavement friction values (*SN40R*, skid/friction number determined with a locked-wheel friction tester operated at 40 mi/hr (64 km/hr) less than 40 for low and moderate traffic levels.

Empirical evidence from these research studies shows that vehicle crashes are more likely to occur on wet pavements (with lower friction levels) as pavement friction levels decrease. Loss of skid-resistance produces a noticeable increase in crash rates. Research also shows that when pavement friction falls below a site-specific threshold value, the risk of wet crashes increases significantly.

The constitutive relationship between pavement friction and wet crashes is site-specific, as it is formulated by introducing not only friction parameters but many others factors as well. An example of such a relationship developed for single carriageways in the U.K. shows that crash risk is seriously reduced as pavement friction increases over normal ranges, as shown in Figure 1 (Viner et al. 2004).

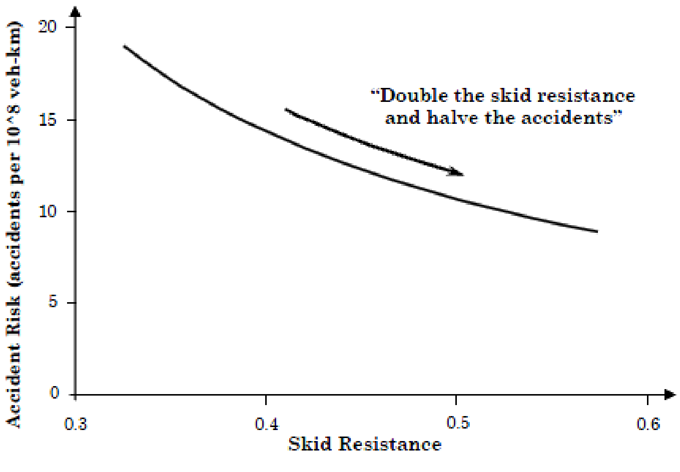

Figure 1: Relationship between pavement friction and crash risk (Viner et al. 2004).

Road slipperiness is an important factor of traffic accidents, especially when the pavement surface is wet. To this regard, statistics of accident data on wet pavements can be used to assess in a quantifiable way the level of insufficiency of friction. A widely known skid-resistance monitoring device, the SCRIM (Sideway-force Coefficient Routine Investigation Machine) - developed and manufactured by the British Laboratory of Transport TRL (Transport Research Laboratory) - is used for measurement of slipperiness

(SFC) on road networks.

Various threshold values for SFC proposed by agencies of USA, UK and Finland are presented on Table 1. Differences among proposed values indicate the absence of a uniform and globally applicable methodology for assessment of minimum levels of suitability.

Table 1: Various limit values proposed for the Sideway Force Coefficient (SFC).

Agency	Country	National network	Regional network
AASHTO	USA	-	-
Maine DOT	USA	0.35	0.35
Washington DOT	USA	0.30	0.30
Wisconsin DOT	USA	0.38	0.38
Minnesota DOT	USA	0.45	0.45
Highways Agency	UK	0.30 – 0.45	0.45 – 0.55
Finnish Road Administration	Finland	0.60	0.40

Another pavement friction study by Wallman and Astrom with similar content and objective is the Norwegian “Veg-grepsprosjektet”. In this study, comprehensive friction features and dynamic traffic characteristics were measured resulting in the assessment of crash rates for different friction intervals as summarized on Table 2 (Wallman and Aström 2001).

Table 2: Crash Rates for Different Friction Intervals (SFC).

Friction Interval (SFC)	Accident Rate (personal injuries per million vehicle kilometers)
< 0.15	0.80
0.15 – 0.24	0.55
0.25 – 0.34	0.25
0.35 – 0.44	0.20

3.2 Relation between Roughness and Users Cost

Pavement roughness is defined generally as the mathematical sum of irregularities on pavement surface affecting ride quality (RQ). Roughness is an important pavement characteristic because it affects not only ride quality but also vehicle delay cost (VDC), fuel consumption and vehicle maintenance expenses. According to a research by the World Bank, pavement roughness is an important factor of ride comfort and users cost (University of Michigan, Transportation Research Institute [UMTRI] 1998).

The international roughness index (IRI), measuring pavement roughness, was developed by the World Bank in the 80’s. IRI (m/km) is used to define the longitudinal profile of a wheeltrack and constitutes a standardized roughness measurement. The open-ended IRI scale for various pavement surfaces is shown in Figure 2.

Various limit values for IRI proposed by road agencies from USA, Canada, Australia and Sweden are shown on Table 3.

Former research on pavement surface characteristics has made an attempt to correlate pavement roughness with accident rate. However, it becomes easily perceptible that even if, in some case studies, a strong relation between accident rate and IRI can be established, this can be hardly considered as a general rule.

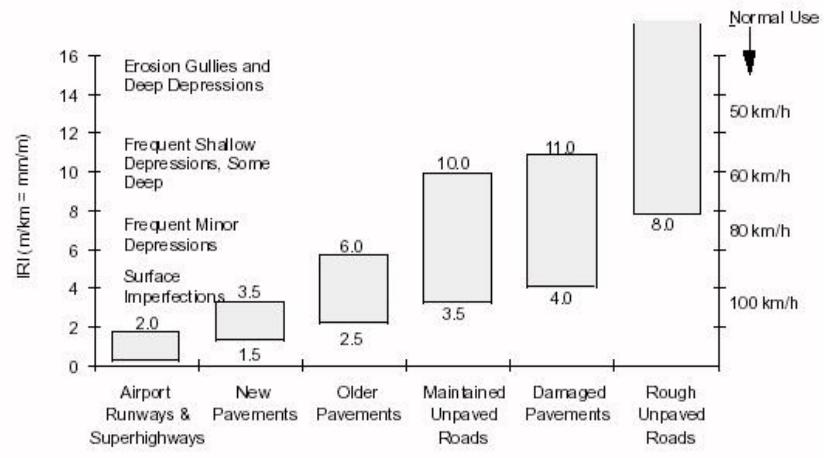

Figure 2: IRI scale (Sayers et al. 1986).

In a research work by the VTI (Ihs and Sjorgen 2003), the impact of pavement irregularities to the cost of time of travel (time travel cost) was investigated. Travel time costs are calculated using a simplified model based on the free speed model presented in HDM-4. The time cost is a function of roughness, speed limit and a "law enforcement" factor illustrating drivers' respect of the speed limit.

Table 3: Various proposed threshold values for IRI (m/km).

Agency	Country	National network	Regional network
FHWA	USA	2.70	3.16 – 3.48
New Brunswick DOT	Canada	2.50	2.50
Alberta DOT	Canada	1.90	3.00
Washington DOT	USA	3.50	3.50
Kentucky DOT	USA	2.73	2.73
Minnesota DOT	USA	1.90	1.90
Indiana DOT	USA	3.20	3.20
Austroads	Australia	3.67	3.67
VTI (Swedish National Road and Transport Research Institute)	Sweden	3-4	3-4

The simplified free speed model equations for private cars and lorries, respectively, are as follows:

$$v_{pc} = \frac{3.6}{\left[\left(\frac{3.6}{HG*LF}\right)^{\frac{1}{0.151}} + \left(\frac{1.5*IRI}{203}\right)^{\frac{1}{0.151}}\right]^{0.151}}, \text{ for private cars}$$

and

$$v_{l} = \frac{3.6}{\left[\left(\frac{3.6}{HG*LF}\right)^{\frac{1}{0.11}} + \left(\frac{1.5*IRI}{203}\right)^{\frac{1}{0.11}}\right]^{0.11}}, \text{ for lorries,}$$

where *HG* is the speed limit and *LF* is the law enforcement factor which in this case is set to 1.

The loss of time is then calculated as follows:

$$t_{loss} = \frac{1}{v_i} - \frac{1}{HG * LF}, \text{ where } i = pc \text{ or } l$$

Finally the travel time cost is calculated using the following time values:
Private cars: 10.88 €/hr and Lorries: 13.60 €/hr.

An example of travel time cost calculated for private cars for speed limit 110 km/h is shown in the figure below.

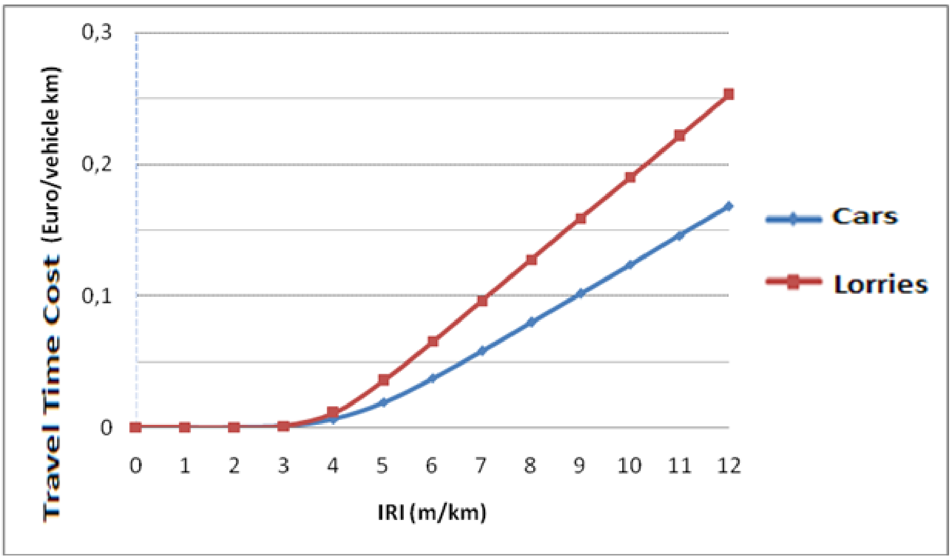

Figure 3: Travel time cost vs IRI for a private car and a lorry, respectively, when the speed limit is 110 km/h.

3.3 Relationship between Rut Depth and Crash Risk

Rutting depth (RD) is an important characteristic of pavement condition which significantly affects ride quality and safety. Maximum acceptable values of RD are generally 12 - 20 mm, limits set by different road authorities according to the road functional category. Higher values of RD indicate functional distress and need for pavement rehabilitation.

Various threshold values for RD proposed by agencies from USA, Canada, Australia and Sweden are shown on Table 4.

Table 4: Various proposed limit values for RD (mm).

Agency	Country	National network	Regional network
AASHTO	USA	-	-
New Brunswick DOT	Canada	20	20
Washington DOT	USA	12	12
Texas DOT	USA	6	6
Minnesota DOT	USA	12	12
Wisconsin DOT	Australia	7.6	7.6
Highways Agency	UK	20	20

In a study analyzing the influence of wheel path depression (WTD) values compared to accident rate (Start et al. 1996), WTD was found to have a negative influence onto number of accidents (Figure 4).

The accident rate seems to be quite insensitive in the 0-to-6 mm zone in the study observations. The accident rate according to Figure 4 increases precipitously at rut depths greater than 6 mm. Although, the important ascertainment is that there is an inflection point of accident rate when rut depth level reaches to 9 mm.

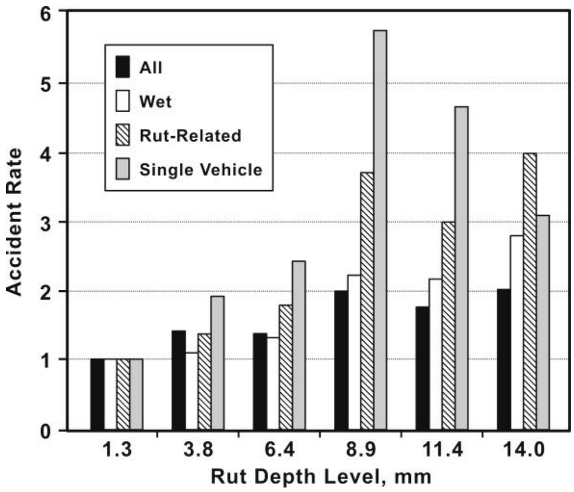

Figure 4: Relative accident rates.

4 LIMIT VALUES OF PAVEMENT CHARACTERISTICS

4.1 Limit Value of SFC

In a study of Highways Agency of UK a strong correlation between SFC and accident rate appears and respective curves are drawn with regard to the minimum radius of horizontal alignment of the road (Figure 5).

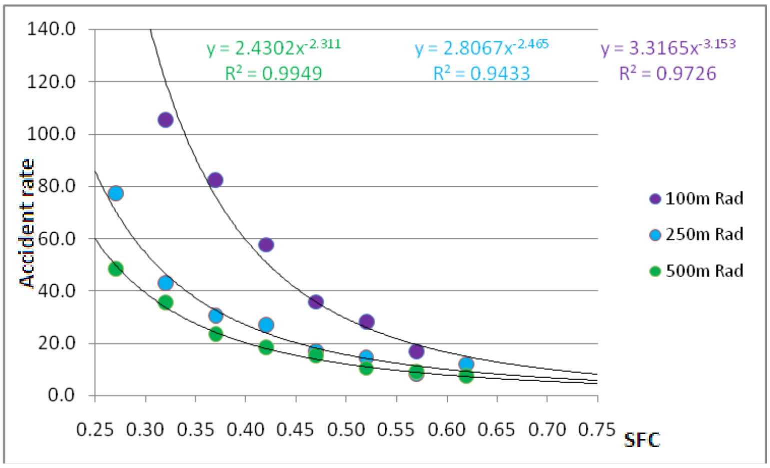

Figure 5: Accident rate related to SFC according for varying radius of curvature.

The mathematical procedure employed to define critical (“inflection”) points on these curves is explained hereafter.

Assuming accident rate is correlated with SFC according to the formula:

$$r(s) = a * s^b \quad (1),$$

where *r(s)* stands for accident rate value, *a*, *b* are constants depending on the radius of curvature and s stands for SFC value. The tangent is given by the first derivative:

$$r'(s) = b * a * s^{b-1} \quad (2)$$

Tangent lines for realistic limit values of *s*, that is, *s* = 0.25 and *s* = 0.75 have gradients (Figure 6):

$$r'(0.25) > r'(0.75)$$

It is assumed that the critical value of *s* is a relation of the upper (*s*=0.25) and lower (*s*=0.75) limits of the function *r(s)*. Attempting to define the critical value of *s*, for which there is an abrupt change in accident rate, the following approach is used:

$$r(0.25) - r'(s) * 0.25 + \beta = r(0.75) - r'(s) * 0.75 + \beta \quad \text{or}$$

$$r(0.25) - r'(s) * 0.25 = r(0.75) - r'(s) * 0.75 \quad \text{or}$$

$$r'(s) = \frac{r(0.75) - r(0.25)}{0.5} \quad (3)$$

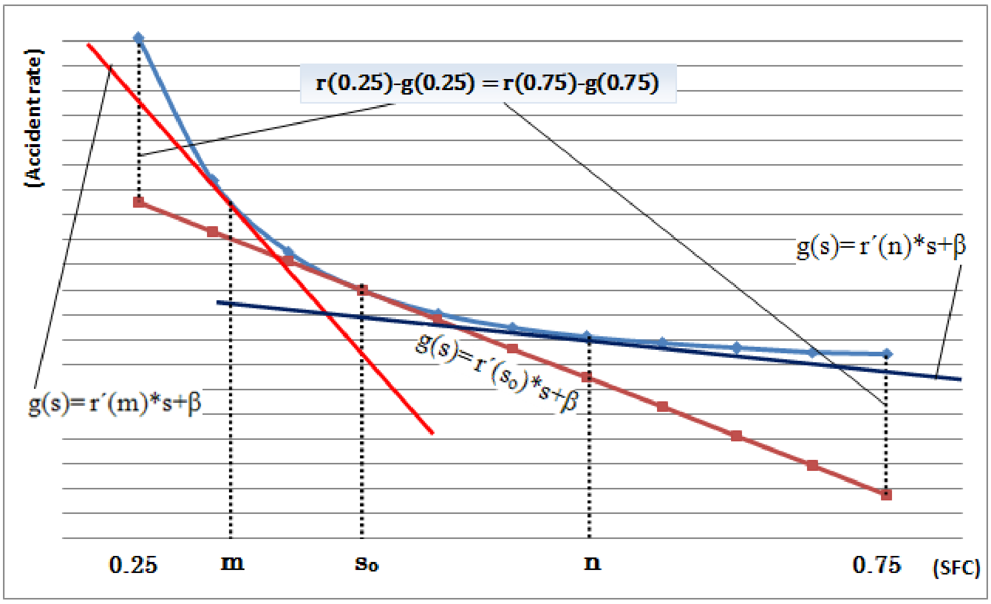

Figure 6: Defining threshold value *s* by relative acceleration rate of accident rate.

So, the critical SFC value is calculated by equations (1) and (3) as follows:

$$s = \sqrt[b-1]{\frac{r'(s)}{a * b}} \quad \text{or} \quad s = \sqrt[b-1]{\frac{2 * [r(0.75) - r(0.25)]}{a * b}}$$

4.2 Limit Value of IRI

The second derivative of the function *T(I)* that expresses the relation between IRI and TTC is a new function, *T´´(I)*, portraying the acceleration of TTC "rate of change". This acceleration is observed to have an absolute maximum. This inflection point yields the critical IRI value. A thorough observation of the evolution of *T(I)* and *T´´(I)* indicates that the absolute maximum is observed when TTC values start to increase noticeably (Figure 7). At this point, the third derivative *T´´´(I)* is equal to 0.

According to the above ascertainment, the limit IRI value is calculated by the following equation:

$$T'''(I) = 0$$

4.3 Limit Value of RD

The methodology to define a threshold value for RD lays on the absolute maximum that the function of accident rate presents for a specific RD value.

According to the methodology proposed for IRI, the RD threshold is calculated by the following equation:

$$r'(d) = 0 \quad ,$$

where *r´(d)* is the first derivative of the function *r(d)* which correlates RD with accident rate (*r*).

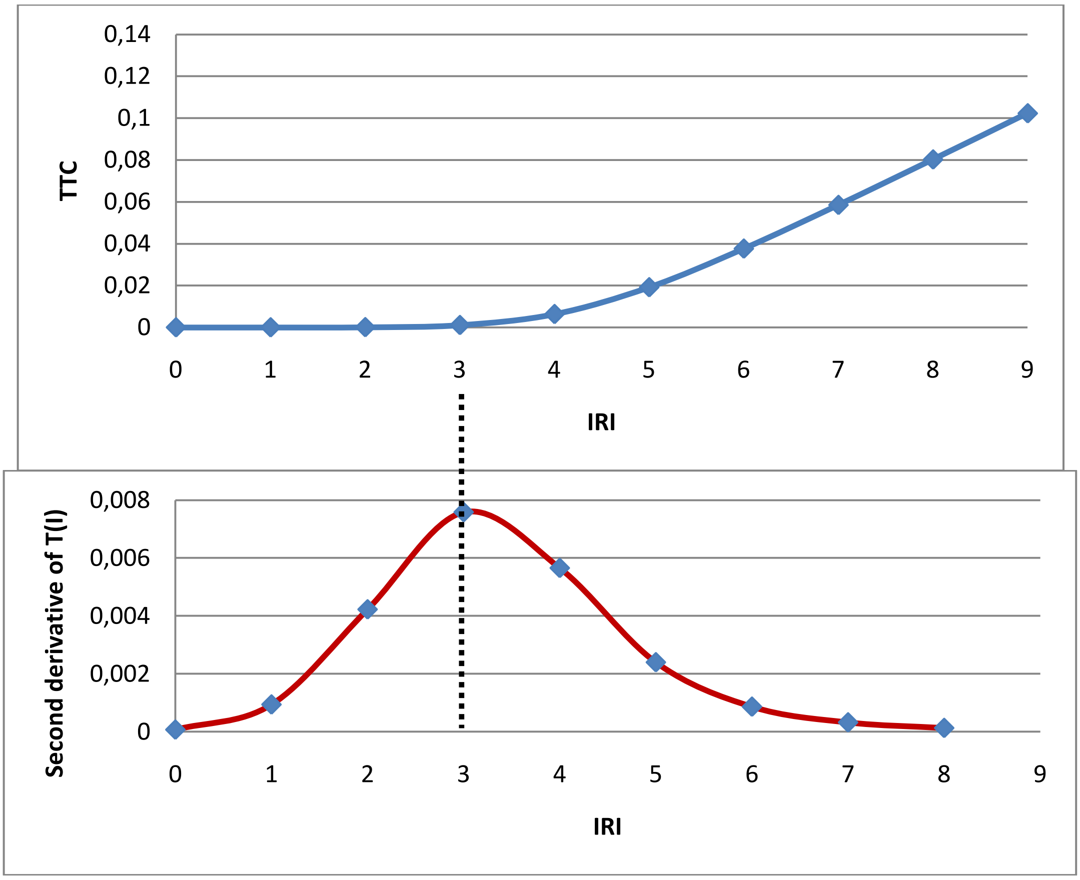

Figure 7: Example of absolute maximum of acceleration rate indicating threshold IRI value.

5 BENEFITS FOR THE ROAD OPERATOR – CONLUSIONS

As it became perceptible, there are specific critical values of SFC, IRI and RD which mark a sudden quantitative change in relative operational criteria, accident rate and users cost. Values beyond critical can lead to significant negative impact to road users and operators. As regards the impact to road users, it is clearly observed that accident rate increases rapidly while SFC (in terms of skid-resistance) reaches a specific critical value. In terms of RD increase, there is a specific critical value to trigger accident rate decrease, indicating the maximum allowable value of RD. As regards the IRI, it is observed that time travel cost suddenly stops accelerating when IRI values attribute to noticeable TTC values. These critical values can be defined as limit allowable values of the pavement performance indicators. The proposed methodology for defining limits of appropriateness can be used as a useful tool for the standardization of allowable values of pavement characteristics based on concrete criteria with direct retributive profit the reduction of accident rate and the minimization of users cost. This objective is achieved by means of systematic road inspection and monitoring and appropriate maintenance and rehabilitation engineering operations with direct beneficial effect to safety and comfort.

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